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Traffic Flow Optimization on Freeways

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Abstract

Intelligent Transportation Systems (ITSs) are advanced technologies and applications integrated in transportation networks with the aim of creating a safe and efficient transportation environment. ITSs are developing both in the cities, that will become smart cities, and on freeways, by designing smart roads. Focusing on freeways, tollbooths currently represent serious challenges in many countries. Most commonly used payment toll systems create traffic congestion with the consequent increase of traffic pollution, time delays and negative results in terms of vehicular throughput and freeways' efficiency. ITSs integrated with new arriving Unmanned Ground Vehicles (UGVs) and novel toll collections designs, such as Open Road Tolling (ORT), could remove, or at least, mitigate these bottlenecks. This paper presents traffic flow models and algorithms implemented in IBM ILOG CPLEX Optimization Studio. Modeling and comprehensive investigation, using real data, brings advantages in terms of traffic throughput and optimization.

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Keywords: Throughput Optimisation; Traffic flow; Open Road Tolling; VANET

1. Introduction

Traffic congestions on the freeways are problems that arise for different reasons. Intelligent Transportations Systems (ITSs) can reduce them and mitigate the negative consequences[2]. ITSs integrated with new technologies can benefit transportation networks in terms of safety improvements[3], traffic flow maximization[4] and gas pollution reduction[2]. According to number of studies[5,6], tollbooths represent one of the major causes of these problems. We could use different mathematical models[7-9] to describe these bottlenecks. Different technologies have been developed, in recent years, in order to increase freeways' performances and offer better level of service (LOS)[6].

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Moreover, new transportation modes, such as applications of Unmanned Ground Vehicles (UGVs), in the near future, integrate their technology with recent tollbooths designs, offering comprehensive solutions[10]. Integrating these technologies will bring important advantages in traffic control and traffic management, creating faster and real-time transportation networks[11]. ITSs, new technologies, transportation modes and infrastructure are components of the transportation network[12], which allow communication and information exchanges between elements inside its environment[3]. Vehicular ad Hoc Network (VANET) is a computer network associated with moving vehicles and road infra-structure. For example, vehicles can already communicate using Dedicated Short Range Communications (DSRCs) in order to improve transportation systems[13] performances. VANET, as an ad-hoc computer network[3] of fast moving nodes, i.e. network elements, is able to support communication and enables guidance of the vehicles that are in its range while moving with high speeds, as defined by Institute of Electrical and Electronics Engineers (IEEE) standards. IEEE 802.20 supports various vehicular mobility classes, up to *250 Km/h* in a Metropolitan Area Network (MAN) environment. This is just an extreme case that shows capabilities of the new technologies, especially in the communications domain. Down to the low speeds, it is evident that integrating these technologies in freeways' bottlenecks, such as tollbooths, will contribute to the creation of safer and better performing traffic on the roads.

Nomenclature

ρ	traffic density
ρ_0	initial density
ρ_{max}	critical density
C_0	signal speed
L	number of lanes distinguished by the payment method
N	total number of vehicles in the time window
q	traffic flow
v_{ff}	free flow speed (i.e. the maximum allowed speed)
T	time window
t	time
v	speed
v_{ff}	free flow speed
y_i	Boolean decision variable. Equals to 1 if the *i*-th vehicle passes through the payment toll in T; 0 otherwise
x	space
Z	decision variable: it represents the sum of all *i*-th vehicles that pass through the payment toll in time T

2. Freeways and toll payments designs

It is important to define different types of toll payment methods adopted in freeways. First of all, toll roads can be categorized according to their payment systems, as explained here:

- *Close Systems* are toll roads with entry and exit barriers. Payment could be made at the entrance, exit or both.
- On the other hand, *Open Systems* present just one barrier at the entrance of the freeway.
- Finally, *Open Road Systems* do not have barriers and payments are received by electronic collection[14].

Thus, considering these three types of roads, each country has developed its own systems for the toll collection. In particular, it is possible to identify two collection methods. Payments by cash, credit cards or special tickets are the most common[6]. These collection systems are still present almost everywhere, but many developed countries are using electronic toll collection. This method presents remarkable advantages, such as costs and congestion reduction, no need for the speed decrease and consequently, no large delays. However, many countries are still using both methods, without achieving total benefits of implementing electronic toll collection. In particular, many European countries use different toll collection techniques, regardless of expectations that a unified system should be used. Thus, this creates a fragmented global European transportation network[15], in which each nation has its own rules and payment systems. Presently, the European Union (EU) is developing a common transportation network, called European Electronic Toll Service (EETS), based on electronic toll collection. The main objective is to develop and implement an efficient and 'without borders' system[16].

2.1. Open Toll Road (ORT) design, approaches and operations

Open Toll Road (ORT) or Free-Flow Tolling refer to toll roads considered already as parts of ITS. The names define exactly the types of tool collection scenarios on the roads. On one hand, the name ORT points out the fact that these roads are constructed without barriers[14]. On the other hand, Free-Flow Tolling stresses on the importance that vehicles pass through the payment without decreasing their speed, thus at the free-flow speed[17]. The free flow speed is defined by government regulations as the maximum speed allowed. This key fact brings the following benefits[18]: congestion minimization, time saving for drivers, cost saving for governments or freeways' managing companies and gas pollution diminution. We have investigated congestion minimization and time saving for the combined tolling systems. Regarding to costs savings, recent studies show that OTRs result in significant cost reduction. Construction costs are decreased due to the fact that toll bridge infrastructures replace common tollbooths. Figure 1 shows the difference between common tollbooths (a) and electronic toll points (b). Moreover, operations and maintenance costs are reduced because the payment systems are completely computerized and wireless data acquisition (DAQ) is performed. Finally, focusing on the economical point of view, nations would benefit from implementing a unique and standard payment toll system[16]. Further, according to other studies [19, 20], OTRs improve air quality and promote 'green transportations systems'[21], which are strictly related to ITS. In particular, researches have focused on carbon monoxide (CO) levels and they conclude that, in theory, it will be possible to reduce CO emission up to 97%[20]. Thus, it is clear that OTRs brings important advantages in multiple spheres of the transportations system and environment protection.

a

b

Fig. 1. (a) Common tollbooth (www.nj.com); (b) Electronic toll bridge (http://www.brisainovacao.pt)

2.2. Electronic Toll Collection (ETC), New Technologies and Future Applications

Electronic Toll Collection (ETC) systems have started developing since William Vickrey, Nobel Economic Prize winner, speculated the use of electronic payment systems in order to avoid traffic congestions in the Washington D.C. area[22]. The first technology adopted, required the users to slow down, up to a minimum limit speed, so that infrastructure i.e. data acquisition system could identify passing vehicle. When the system detects and communicates with the vehicles, it automatically opens the bar, allowing the vehicle to pass through the tollbooths. In the most recent systems there are no such limitations and vehicles do not slow down for tooling. This is the case of Open Road Systems, which allow a constant free flow, resulting in all the benefits mentioned before. Presently, two systems for Automated Vehicle Identification (AVI) are used worldwide. The first technology consists of two systems – an antenna at the toll point and a transponder installed on vehicles – which communicate using Dedicated Short Range Communications (DSRC). The transponder can be referred to as an On Board Unit (OBU)[23]. These two systems typically connect through the selected radio frequency (RF) channel, resulting in a reliable and efficient system operation. The transponder and the antenna are part of the transportation network and they represent a moving node – the transponder – and a fixed node – the antenna – of VANET[3]. While economic and environmental advantages are proved, this system also presents two disadvantages: a cost increase for freeways' users and difficulties in identifying toll evaders. Drivers have to pay and install transponders at their own expense and this could result in an effectiveness deficiency when governments or municipalities decide to switch from old non-electronic system to ETC. Furthermore, the majority of transponders, Radio Frequency Identification (RFID) tags, can be transferred from one vehicle to another with difficulties in recognizing toll evaders. In some countries, transferring those electronics tags (etags) is allowed, as long as they are registered to more than one vehicle. The best practice is to have a dedicated etag per each vehicle.

The second ETC system, the Automatic Number Plate Recognition (ANPR), does not create a communication between the moving node and the fixed infrastructure. Using cameras, it reads vehicles plates and then addresses the toll payment directly to the user (i.e. the vehicle's owner). The system includes a series of cameras that detect plate numbers through optical character recognition (OCR). After this first step, the system identifies the vehicle's owner and send him/her the payment bill[24]. This ETC technology brings multiple advantages: users' costs reduction, users' willingness to adopt this system and reliable identification of vehicles' types. In fact, users do not have to buy a compulsory device, resulting in a positive user behavior. However, studies[24, 25] conclude that APNR has high operational costs that do not justify its use. In the tooling systems that relay on RFID identification, as the most reliable, image recognition is used as a backup system only when passing vehicle does not have tag installed. In that case charges to the car owner are higher.

All those new technologies are primarily trying to optimize the actual services in order to improve the traffic throughput and tooling reliability[26]. Considering the popularity of smartphones, IT companies have developed mobile applications that directly communicate with tooling system antenna, providing the user with real-time information on toll payments through push notifications. Theoretically, this technology could solve problems related with ETC, offering high flexibility to users, which do not have to buy an OBU, and reliability, associated with low cost, for roads' managing companies[27]. This might be one of the optima solutions. Mobile phone applications have already entered into many engineering, science, medical and other domains.

3. Traffic Flow: Theory and Algorithms

Three methods of traffic analysis, based on the level of scale and complexity, have gained importance from the 1950s. The microscopic scale relies on fluid dynamics models. The macroscopic scale is based on partial differential equations (PDE). Kinetic scale expresses traffic theories using probability and statistics. Our research focused on the microscopic model, since it brings particular advantages in describing traffic jam and bottlenecks.

Most important traffic flow theories are based on three parameters[28, 29]: flow (q), density (ρ) and speed (v). Flow defines the number of vehicles passing through a particular point in the unit of time [No/s]. Density is defined as the number of vehicles in the unit of length [No/Km]. Speed refers to the mean speed of the traffic flow measured in [m/s] and it is function of the density[28]. Theory formulation started in 1950 when M.J. Lighthill, G.B. Whitham and P.I. Richard described their theory using fluid dynamics flow rules and laws, and applying them to traffic studies[30]. In particular, they stated that traffic flow is a conserved process. Applying a fluid flow analogy, they wrote the non-linear scalar conservation law for traffic, as shown in equation (1):

$$\rho_t + q(\rho)_x = 0 \tag{1}$$

In this formula it is important to notice that the flow *q(ρ)* is function of the density, *ρ*, which also is function of the time (t) and space (x). This formula represents the basis for any further study. Moreover, the inverse of the flow (1/q) describes the space-time between the *i*-th vehicle and the (*i*+1)th vehicles that pass through a reference point. This parameter is called headway and it is particularly useful in representing and modelling traffic congestions[17]. Using the conservation law of equation (1), it is possible to refer it to two states, which in traffic models are two arbitrary positions (x_1 and x_2), as expressed in equation (2).

$$\frac{d}{dt}\int_{x_1}^{x_2} \rho(x,t)\,dx = q\big|_{x=x_1} - q\big|_{x=x_2} \tag{2}$$

This expression is useful for the aim of our investigation. In fact, the left side represents the increase in the number of cars and the right side the flux before and after two points, which represent an arbitrary points before the tollbooths and after the payment. The following equation (3) rewrites the previous equation as a PDE:

$$\frac{\partial \rho}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad \Leftrightarrow \quad \rho_t + q_x = 0 \tag{3}$$

As said before, speed depends on density and equation (4) describes this relation:

$$v(\rho) = v_{ff} \cdot \left(1 - \frac{\rho}{\rho_{max}}\right) \tag{4}$$

In equation (4) v_{ff} is the free flow speed and ρ_{max} represents the critical density[28]. It means that if $\rho < \rho_{max}$, there is no congestions and if $\rho \geq \rho_{max}$, the bottleneck is forming jams. Thus, considering an initial density (ρ_0), the traffic problem has this system of equations:

$$\begin{cases} \rho_t + q(\rho)_x = 0 & x \in \mathbb{R}, t > 0 \\ \rho(x, 0) = \rho_0(x) & x \in \mathbb{R} \end{cases} \tag{5}$$

Differentiating for t, the problem (5) leads to the solution expresses in equation (6):

$$\rho_x x'(t) + \rho_t = \rho_x\left(x'(t) - q'(C_0)\right) = 0 \tag{6}$$

C_0, known as signal speed[1], represents the wave front velocity at which shockwaves propagate their effects on following vehicles.

In order to solve these equations, cumulative vehicles count curves, sometime referred as N curves, can be used. They describe the totality of vehicles in the system that want to go over the toll payments in a certain time (i.e. the time window), and the real number of users that are able to do so[31]. Three curves - arrival, virtual and departure curve – define the traffic situation at bottlenecks in N curves. The arrival curve shows the vehicles at time T, the virtual curve represents the number of vehicles that do not experience delay and the departure curve shows the real traffic throughput considering the queue that it may form at the bottleneck. N curves allow to conduct a mathematical model that requires these assumptions: constant deceleration for all vehicles, constant payment times, no human errors or system failures. Thus, despite some human behaviour, such as time reaction[32], and a differentiation between cars and heavy vehicles are considered, other factors, such as drivers' age and experience are neglected. Considering that in 2017 UGVs will appear on highways[33], these assumptions explore their positive effects on transportation networks. In fact, UGVs can overall travel at constant speed, reducing variations and deviations from mean value for parameters, such acceleration and deceleration.

4. The Study Case: BREBEMI

This paragraph introduces the case study chosen, explaining the freeway's layout, showing 2015 data and forecasts for the next ten years.

4.1. Real Life Example: Key Facts and Data

BreBeMi (Brescia-Bergamo-Milano), also known as A35, is an Italian highway that connects the city of Brescia with Milan, passing through the Bergamo province, in north Italy[34]. It presents three lanes in each direction with a regular flow of 40,000 vehicles/day. BreBeMi was the first Italian freeway realized in project financing, without Government and State contributions, and it cost totally 1.61 billion of euros[35].

BreBeMi S.p.A.[34] provided data collected in 2015 and it predicted a five percent vehicle increase in the next 10 years. Table 1 shows data and forecast results for years 2016, 2019, 2022 and 2026. According to the data analyzed, the tollbooth in Liscate, the closest one to Milan, is the freeway's bottleneck. The tollbooth experiences two high-demanding times (i.e. peak hours) – 7:30-9:30 am and 4:30-6:30 pm – that represent the time-window for the analysis.

Table 1. Data and forecast for the BreBeMi freeway

Daily flow	2016	2019	2022	2026
Total number of vehicles	40,000	46,305	53,604	65,156
Total number of vehicles in Liscate in the pick hours	6,000	6,946	8,041	9,773

5. Traffic Throughput Maximization

This study analyses three cases in order to show throughputs. The mathematical model considers many parameters to create a correct and reliable simulation. In particular, it was necessary to understand constraints for all three models, formalizing criteria and constants, and defining decision variables. In order to solve the problem, IBM ILOG CPLEX Optimization is used. This software requires[36] data and variables declaration, objective functions and constraints. Maximizing the throughput is the objective function. Table 2 shows all the objects, parameters, constants, variables and data used.

Table 2. Mathematical model's input and outputs

Decision variables and Data	Nomenclature	Value (cars/trucks)	Unit
Total number of vehicles with Telepass	N'	4,200 in 2016	-
Total number of vehicles without Telepass	N''	1,800 in 2016	-
Time window	T	7200	s
Number of lanes (Telepass/Cash)	L (L_p/L_c)	-	-
Free Flow speed	v_{ff}	130/110	Km/h
Maximum speed in the payment lanes	v_{pay}	30	Km/h
Time between vehicles	T_{BV}	-	s
Time for make a non electronic payment	T_{pay}	10	s
Boolean variables	y_i	1 if the *i*th vehicle passes; 0 otherwise	-
Time at which each vehicle passes through the tollbooth	T_i	To be found	s
Throughput	Z	To be found	No. of vehicles

5.1. The Mathematical Model

The mathematical model, used to describe the traffic throughput, implements the data in an iterative algorithm that stops when it reach the optimal solution. The model states to find the maximum throughput, as equation (7) shows:

$$Maximize\ Z = \sum_{i=1}^{N'} y_i \cdot L_p + \sum_{i=1}^{N''} y_i \cdot L_c \quad (7)$$

The time at which each vehicle passes through the tollbooth is an important parameter because it describes the efficiency of the system and sets the upper bound time constraint. Equation (8) defines T_i as a decision variable of the algorithm. Naturally, T_i depends on T_{BV} (time between vehicles), which is expressed in equation (9) and it is function of the traffic flow. In equation (9), constants are all data such as mean time for payments, mean deceleration time, traffic flow and density during peak hours that we received from BreBeMi S.p.A. However, it is important to state that these values can be modified and adapted to other real life examples[32].

$$T_i = y_i \cdot T_{BV}(i - 1) \quad (8)$$

$$T_{sv} \quad \frac{1}{q} + constants \quad where\ q \quad q(x,t) \tag{9}$$

Finally, inequality (10) sets the time limit and the algorithm is forced to stop when the time window is reached:

$$\sum_{i=1}^{N} T_i \leq T \tag{10}$$

5.1.1. Case A: The Present Situation

The tollbooth in Liscate presents 6 lanes; four are dedicated to Telepass and 2 to cash payments. The technology of Telepass works only in closed roads with barriers both at entrance and exit. Moreover, Telepass lanes allow a maximum vehicle's speed of 30 km/h for safety reasons[37]. Finally, cash lanes represent the real critical bottlenecks because vehicles must stop for payment and have to wait for receipts, or change. These procedures form shockwaves that result in traffic congestions. Thus, the mathematical model for vehicles with Telepass should consider times to reduce speed, times to pass through the tollbooths and any delays. Vehicles that pay by cash should add the time to stop and pay, which results in more critical shockwaves.

5.1.2. Case B: Four Telepass Lane

This model presents fewer constraints than Case A because it proposes to replace the cash lanes with other two Telepass Lane. This solution involves that all users have a Telepass system installed. However, this proposal would only be feasible if Italy adopted a unique toll payment system or if Europe imposed to its State Members the introduction of EETS [16]. Thus, this mathematical model considers the slowing down time from the free flow speed to 30 km/h as the main constraint.

5.1.3. Case C: An Open Road Toll Design

The last model suggests the introduction of tollbooths without barriers in order to avoid speed reduction and travel at the free flow velocity. This design involves the same complications discussed for case B. Thus, this mathematical model does not present speed constraints – except for the maximum free flow speed allowed – and, in order to show the ORT benefits, the algorithm considers only 3 lanes, instead of the six existing.

5.2. Results and Comparisons

CPLEX solves the algorithms for the three cases in respectively 98, 75 and 48 seconds for the year 2016 with small timing increments for 2019, 2022 and 2026. Table 3 and figures 3,4 and 5 show the differences of the three models in terms of vehicles' throughput. In particular, it is relevant to point out that Case A is not able to satisfy the demand because of the bottleneck created in the cash lanes that continuously expand traffic congestions during peak hours.

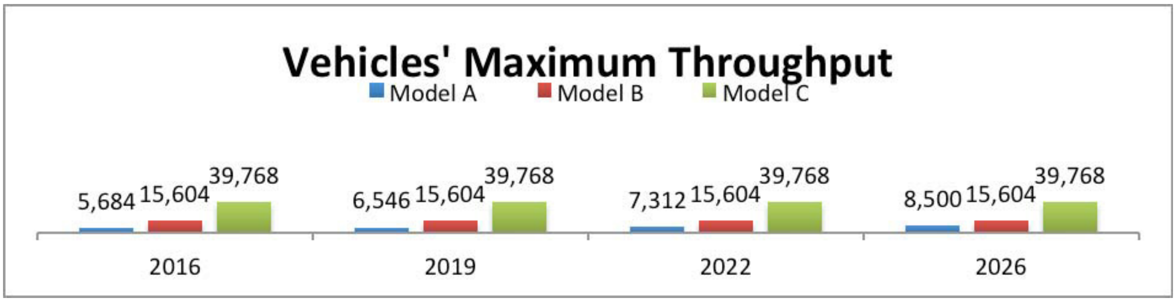

Fig.3. Throughput results

Table 3. Results

Vehicles' throughput	2016 (6,000 veh/2hrs)	2019 (6,946/2hrs)	2022 (8,041/2hrs)	2026 (9,772/2hrs)
Model A	5,864	6,546	7,312	8,500
Model B and C	6,000	6,946	8,041	9,772

Table 3 and figure 3 show that model B and C have outstanding results in terms of vehicles' throughput and both of them can achieve the maximum vehicles' capacity required for each year, with a respectively maximum of 15,604 and 39,768 vehicles during peak hours. In particular, considering 2026, which is the year with the highest forecast, model B is able to almost double the maximum capacity and model C can achieve four times the throughput required. Thus, it is important to notice that model B suggests that introducing a unique electronic collection system has particular benefits. The mathematical model of case C implies that ORTs represent the most performing systems and these types of transportation network have the best result and output in terms of vehicles' throughput and environmental issues. Moreover, the result obtained shows that BreBeMi was correctly designed and constructed[6]. Since the freeway presents the same characteristics – number of lanes, no tunnels and constant slope – for all of its length, it is possible to conclude that BreBeMi could achieve important results switching from the present toll collection system to ETC. On the other hand, figure 4 shows limitations of the present system. Focusing of 2026, it is possible to observe that more than 1,200 vehicles, which represent the 13% of the vehicles during peak hours, cannot pass through the tollbooth in the time window. Moreover, the mathematical model underlines that the presence of cash lanes creates the tollbooth bottleneck.

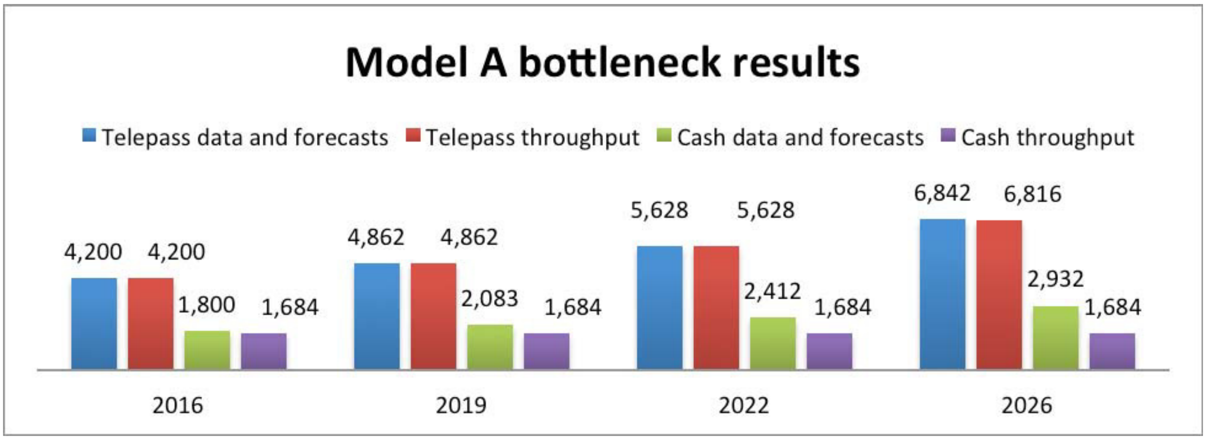

Fig. 4. Model A bottleneck

6. Conclusion and Future Work

We have presented different toll payment methods, showing benefits and disadvantages that each technology brings into the transportation system. The study presented in this paper shows the importance of communications and the need to integrate different technologies and procedures together in order to develop ITSs. Using a real life example, we investigated the benefits associated with ETC in term of vehicles' throughput on freeways. ETC technology is already available but it still carries problems and issues that limit its applications and outbreak. Despite that the benefits of introducing ORT systems are evident and undeniable, further research in the technology implementation should be conducted. In particular, future studies should focus on technologies that avoid using OBUs and allow an absolutely reliable detection of vehicles, in order to avoid toll evaders and failures in the system. Finally, we highlight the importance and the necessity to adopt a common toll payment system in the whole Europe. This investigation strongly supports the idea of the European Electronic Toll Service (EETS) and it has shown economic, environmental and social advantages in establishing this solution in EU. Further analysis should clearly state and demonstrate that EU nations, with the aid of European public funds, would have commercial and economic benefits, which could ensure a self-financing and a short payback period for this technology widespread implementation.

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